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Damage and Marginal State of the Constructional Materials under the Complex Low-Cycle Loading Conditions.

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ABSTRACT: *The paper has presented the results of the theoretical and experimental investigation of the limited state criteria for several structural steels and alloys, subjected to nonproportional low-cycle loading. The new generalised type of the kinetic equation of damage of the materials has been proposed. The limits of the usage of the proposed equation has been checked on the base of the experimental data obtained on the tubular specimens tested in low-cycle fatigue regime on piece-wise linear trajectories of loading.*

Notation

Ω - scalar, that depends from the history of loading;
L_p - Odquist's parameter;
N_p - number of cycles to failure;
ρ_{ij} - microstresses;
ρ_i - intensity of microstresses;
q - internal time;
A_i - some constants;
D - some function of physical parameters;
S_0 - strength limit for equal three axial tension;
σ_{eq} - equivalent stress;
ε_{eq} - equivalent deformation;
ν - Poisson's ration;
e_p - limited plasticity of the material for static proportional loading;
ε_p - amplitude of plastic deformation;
χ - Pisarenko - Lebedev ratio;
W_p^k - energy of normal microstresses;
W_{eq} - equivalent energy of microstresses;

ε_{ij}, γ_{ij} - amplitudes of strains;
σ_{ii}, τ_{ij} - amplitudes of stresses.

Introduction

Structural elements of the modern technical devices are usually subjected to severe pattern of thermo-mechanical loads. Their lives highly depend on the low-cycle fatigue resistance under nonproportional loading (N.A.Makhutovtov et al., 1983, A.N.Gusenkov et al., 1979). The investigations, which had been conducted in the previous years (see, for example, the reviews (A.N.Gusenkov et al., 1979, V.A.Strizhalo et al., 1987, A.N.Romanov, 1988)), had been concentrated on the studies of the damage processes during the low-cycle loading, mainly for simple proportional trajectories of the loading.

It has been stated (V.V.Novozhilov, 1972, O.G.Rybakina, 1969, Yu.G.Korototkich, 1985) that the processes of inelastic deformation and damage of the structural materials are interconnected. However, the majority of the proposed damage accumulation criterias has not taken into account the elasto-plastic constitutive equations of the material behaviour and defence of the damage process on the history of elasto-plastic loading. The investigators usually have left aside such important factors as brittleness of the material, which appears during deformation and microcrack closure. Both of the mentioned effects can develop from the first cycles of the elasto-plastic deformation and can highly influence on the damage process.

Kinetic equation of damage in energetic interpretation

It has been assumed in damage theory that the phenomenological parameter in general is a tensor, depending from the deformation path. Such an approach complicates practical application of this type of criteria.

In general the damaged state, when described with the tensor parameters, could be estimated by some scalar, which depends from the history of loading:

$$\Omega = \Phi(L_p, \Omega)\big|_{N_p} = \Omega^* \qquad (1)$$

where $L_p = \int (\frac{2}{3} de_{ij}^p de_{ij}^p)^{1/2}$ - Odquist parameter, N_p - number of cycles to failure, Ω^* - critical value of the scalar, which corresponds to failure. By this approach it is possible to describe damage of the materials, using some physical parameters, and obtain satisfactory results of calculations (V.V.Novozhilov, 1972, O.G.Rybkina, 1969, A.A.Iljushin, 1963).

At the same time it has been shown in (V.V.Novozhilov, 1972, O.G.Rybkina, 1969) that more precise evaluation of the lifetime could be obtained by using kinetic equation of damage accumulation and criteria that were suggested in (V.V.Novozhilov, 1972, O.G.Rybkina, 1969). It was suggested, that it was existed microstresses ρ_{ij}, which were responsible for the appearance of the microdefects, and energy of fracture is proportional to the work of microstresses on the plastic deformations. Taking into account main parameters of microstresses on the low-cycle loading, the kinetic equation of the damage accumulation could be presented in the way:

$$\frac{d\Omega}{dq}=A_1D^{A_2}+A_3\Omega, \tag{2}$$

Here A_1, A_2, A_3 - some constants, q - internal time (either number of cycles to failure N_p, or length of the curve of the plastic deformation), D - some function of physical parameters, which describe the damage process. Scalar parameter Ω in equation (2) allows to take into account influence of the previously accumulated damage from the beginning of the process of cyclic deformation to the current moment of internal time or number of cycles. This part of the equation gives more adequate description of the development of the damage process, up to the limited state of the material. It has been considered that for initial (undamaged) state while $q = 0$, $\Omega = 0$, and for the moment of failure, when $q = q^*$, we can assume that $\Omega = \Omega^*$. Initially it has been assumed that $\Omega = 1$. But for more precise description of the failure, taking into account that tension ant torsion are the two mechanisms of the damage, it has been suggested (V.V.Novozhilov, 1972):

$$\Omega^*=\frac{S_0^2}{\sigma_{eq}^2}-1, \tag{3}$$

where S_0 - strength limit for equal three axial tension, which do not involve plastic deformation, σ_{eq} - equivalent stress, that could be defined as:

$$\sigma_{eq}=[\sigma_1-\nu(\sigma_2-\sigma_3)], \tag{4}$$

where σ_1, σ_2, σ_3 - principal stresses, ν - Poisson's ratio.

The value of S_0 could be determined by the indirect method on the base of the experimental data for two types of the tests: static proportional loading and strain control low-cycle loading. Then the relationship for the determination of S_0 could be expressed in the way:

$$S_0 = \frac{(4N_p \varepsilon_p^2 - e_p^2)\sigma_{eq1}^2 \sigma_{eq2}^2}{4N_p \varepsilon_p \sigma_{eq2} - e_p \sigma_{eq2}}. \qquad (5)$$

Here e_p - limited plasticity of the material for static proportional loading, ε_p - amplitude of plastic deformation during cyclic loading, N_p - number of cycles to crack initiation, σ_{eq1}, σ_{eq2} - equivalent stresses in first and second types of the tests respectively, ρ_i - intensity of microstresses.

Kinetic equation in the form (2) is quite general and incorporates several criteria, which were suggested earlier.

Thus,

a) if we assume that $A_3 = 0$, $q = N$, $D = \Delta\varepsilon_{eq}$ - we obtain Coffi-Manson criterion (S.Manson, 1966):

$$N_p = A_1 \Delta\varepsilon_{eq}^{A_2}, \qquad (6)$$

b) if $A_2 = 1$, $q = L$, $A_3 = 0$, $D = \rho_l$ - then we obtain equation that were suggested by V.V.novozhilov and O.G.Rybakina:

$$\Omega = A_1 \int \rho_i dL, \qquad (7)$$

c) for $A_3 = 0$, $q = N$, $D = W$ - we have Garud equation (Y.S.Garud,1979):

$$N_p = A_1 W^{A_2}. \qquad (8)$$

For the determination of the deviatoric microstresses a multy surface theory of plastic flow (Z.Mroz, 1969) has been used. The limited surfaces were chosen in terms of Pisarenko-Lebedev equation (G.S.Pisarenko et al., 1975):

$$\chi f(\sigma_{ij} - \rho_{ij}) + (1 - \chi)(\sigma_1 - \rho_1) - \sigma eq = 0, \qquad (9)$$

where $\chi = \sigma_p^T / \sigma_c^T$, $(0 \le \chi \le 1)$ - ratio of the yield limits for tension and compression respectively. If $\chi \neq 1$ the equation (9) takes into account the first invariant of stress tensor. The proposed theory has been used for the calculations of the energy of microstresses, and low-cycle fatigue curves were drawn. For different stress states and different trajectories of loading this curve has not been coincided (N.I.Bobyr et al., 1991). It was found that this feature is charactiristic for several tested materials. To overcome this effect it was suggested to take into account dependence of the energy of microstresses on the stress state. This dependence could be determined experimentally. For tension-torsion tests, conducted on the tubular specimens the energy of normal; microstresses W_ρ^n and energy of shear microstresses W_ρ^k are connected by the relationship:

$$W_{eq} = [(W_\rho^k)^a + b(W_\rho^n)^a]^{1/a}, \tag{10}$$

where a and b some constant. Their values could be determined from the system of the non-linear equations, obtained for different lifetimes. As a result, a uniform low-cycle fatigue curve has been obtained. For further calculations the function D in equation (2) should be replaced by W_{eq} - equivalent energy of microstresses.

The application of the proposed kinetic equations end fracture criteria has been verified for the wide range of nonproportional trajectories of loading shown on the Fig. 1. $S_1 = \sigma_{ZZ}$; $S_3 = \sqrt{3}\tau_{Z\theta}$; $\exists_1 = \varepsilon_{ZZ}$; $\exists_3 = {}^{\gamma_{Z\theta}}\!/\!\sqrt{3}$ - Iljushin co-ordinates, calculated from the applied amplitudes of stresses σ_{ZZ} and $\tau_{Z\theta}$ amplitudes of strains ε_{ZZ} and $\gamma_{Z\theta}$. Tests were conducted on the tubular specimens from the steel 14Kh17H2 and titanium alloy VT14 under stress and strain controlled regimes at the temperature T=293K. The symmetric cycle of loading has been applied in all tests. The experimental techniques and details of the procedure has been decried in (N.I.Bobyr et al., 1991). The parameters of the loading were chosen $\omega_3 = \pi/3$, $\theta_3 = \pi/2$. The microcracks initiation has been determined by two criteria values of $\Omega^* = 1$ and $\Omega^* = \dfrac{S_0^2}{\sigma_{eq}^2} - 1$.

The values of S_0 and constant parameters are given in Table 1.

For the tested materials and different trajectories of loading the uniform low-cycle fatigue curves were obtained. The values of the parameters a and b in equation (10) are given in Table 1.

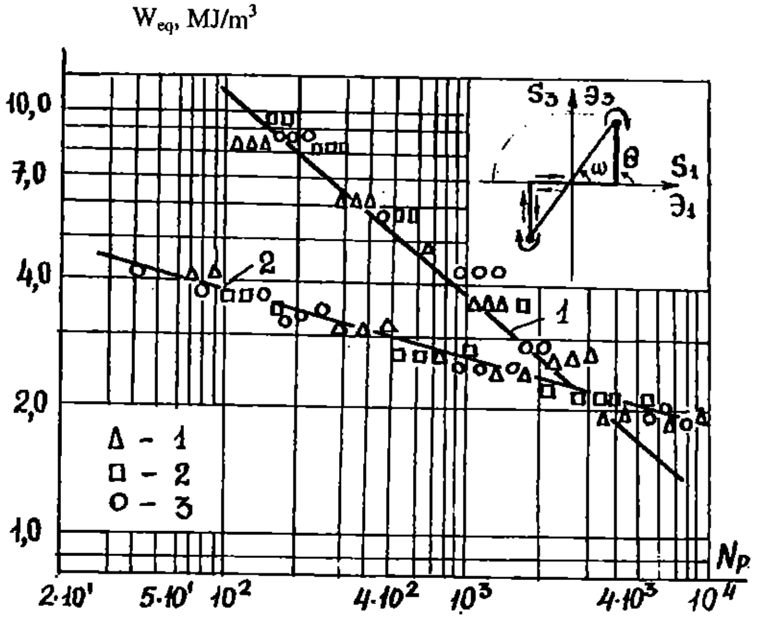

Fig.1. Uniform low-cycle fatigue curves for 14Kh17N2 steel (stress control loading) and VT14 alloy (strain control loading): 1- $\omega=0$, $\theta=0$; 2- $\omega=\pi/3$, $\theta=0$; 3- $\omega=\pi/3$, $\theta=\pi/2$.

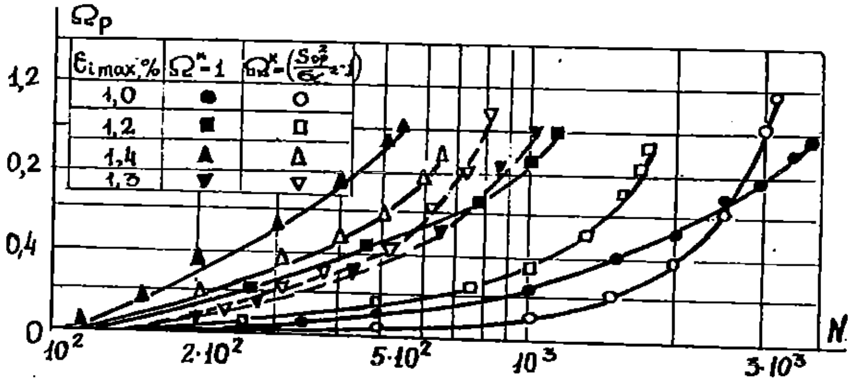

Fig.2. Fatigue damage accumulation curves for VT14 alloy and 14Kh17H2 steel (dashed lines) under complex low-cycle loading.

Table 1. The values of S_0 and constant parameters.

	BT-14		14Kh17H2	
	$\Omega^* = 1$	$\Omega^* = \frac{S_0^2}{\sigma_{eq}^2} - 1$	$\Omega^* = 1$	$\Omega^* = \frac{S_0^2}{\sigma_{eq}^2} - 1$
A_1*10^{-2}	0.310	0.113	2.390	3.166
A_2	3.500	3.500	2.494	2.494
A_3	$0.948*10^{-2}$	$0.298*10^{-2}$	$1.390*10^{-8}$	$7.212*10^{-4}$
a	1.432	1.432	1.397	1.397
b	1.912	1.912	4.795	4.795
S_0 [MPA]	1040.0	1040.0	979.0	979.0

The theoretical and experimental investigations have allowed to find the regularities of the microdamage accumulation for several materials and different trajectories of loading. The comparison of the experimental and calculated data for complex low-cycle deformation and different amplitudes of equivalent stresses has shown good correlation. The difference between calculated and experimental fatigue lives has not exceed 14%. The conclusion can be made that the proposed approach allows to describe the process of damage accumulation ant to predict the fatigue lives of the materials (in the term of failure crack initiation) for complex low-cycle loading.

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